Interstellar Magnetic Field Studies and Requisite Detector Properties

Dan Clemens (Boston University)

Introduction (and take-home message)

Magnetic fields may play central roles in the cycle of matter and energy in the interstellar medium (ISM), especially in star formation processes. To date, there has been no comprehensive survey of magnetic fields in the cold molecular ISM capable of revealing the context and details of the fields.

Magnetic fields may be traced using the Zeeman and Faraday effects at radio wavelengths and using linear polarization of background starlight (optical and near-infrared) and thermal dust emission (FIR and submm). However, only thermal dust emission polarization can probe deeply into the star forming clouds and trace magnetic fields in the cold ISM to kpc distances in the galaxy.

A large-scale survey of the inner regions of the Milky Way, of nearby examples of star forming clouds, and of the enigmatic infrared cirrus to reveal the properties of the magnetic field in the galaxy is a perfect match to NASA's Small Explorer (SMEX) program. Nevertheless, polarization observations place difficult requirements on instruments, on operations, and especially on detectors.

In addition the the usual need for high quantum efficiency, low dark current, and high pixel count, polarization observations require unusually high signal-to-noise (in the range 150-1000:1), good photometric stability, and good immunity to charged particles.

Further, FIR polarimetry surveys conducted from SMEX or MIDEX platforms must contend with limited cryogen lifetimes, mass and volume limits, as well as cost and schedule constraints. My teams have developed SMEX proposals to conduct such surveys, including modeling detector characteristics in the space environment and fold these into realistic mission/survey scenarios.

The most recent of these efforts was called M4, for the Milky Way Magnetic Field Mapping Mission. M4 would feature a 20cm cold telescope, twin 32x32 Ge:Ga photoconductor arrays operating broadband near 95μm, a rotating half-wave plate and fixed wire grid for polarization analysis, and a short 3-4 month lifetime in its 500km altitude sun-sync orbit. Despite high marks for science, technical and mission implementations, the proposed SIRTF/MIPS detector arrays have not been operated in a polarimeter and shown to meet our S/N requirements.

What properties do we need in a detector to win our SMEX and conduct large-scale surveys of magnetic fields in the galaxy?

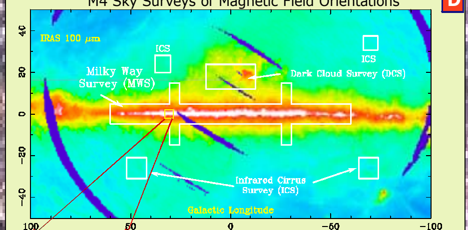
- Large pixel count (32x32 or higher)
- FIR wavelengths (70-200μm) with wide bandwidths ($\lambda/\delta\lambda$ < 3)
- Low read noise (< 150 e/pixel/read)
- High QE (> 10%)
- High dynamic range (> 150:1)
- High achievable S/N (> 150:1 req'd; 1000:1 goal)
- Good photometry (correctable to 1%; differential polarimetric observations intrinsically boost this to 0.1% for polarization values under 10%)
- Operation at SFHe temperatures (1.5-2K)
- Operation over a wide background range, from Galactic Center (20,000 MJy/sr) to IR cirrus (1-10 MJy/sr)
- Capable of simple, robotic, autonomous operation
- Good immunity to charged particles
- Good gain stability and/or recalibration stability

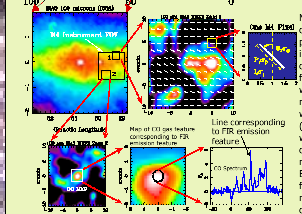
Magnetic Field Questions

The central goal of M4 is to determine the magnetic field structure in the interstellar medium of the Milky Way Galaxy. Meeting this goal rests on answering four broad questions:

1. Are molecular clouds threaded by a common, Galactic magnetic field?
2. What role does the magnetic field play in the diffuse interstellar medium?
3. Are magnetic fields strong or weak relative to the energies and forces affecting molecular clouds?
4. How do magnetic fields thread star-forming regions?

M4 Sky Surveys of Magnetic Field Orientations





M4 will survey a large portion of the inner Milky Way, as shown projected onto the IRAS 100μm image. (Left) The large M4 field of view measures magnetic fields for many regions at once. M4 will measure total surface brightness and polarization properties with a small, 2 arcmin pixel size. (Bottom) M4 FIR emission regions will be kinematically tagged to develop distances, using existing mm molecular line survey data. Bottom panels show how a FIR feature is morphologically matched to a CO feature having a distinct radial velocity.

Survey Data Set Characteristics

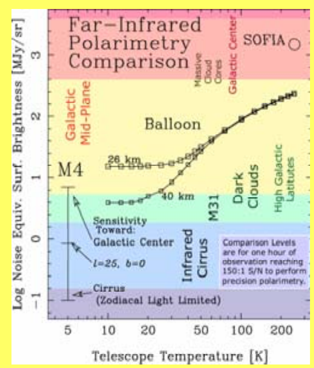
Answering these questions requires surveying many positions within dusty molecular clouds in the galaxy for the weak signature of FIR linear polarization. Some of the data requirements include:

–B-field Orientations – must be able to measure magnetic field orientations to under 10 degrees position angle uncertainty

–Area Coverage – tens of degrees of galactic longitude and latitude to be able to sample hundreds of molecular clouds and to test large-scale effects like the Parker Instability

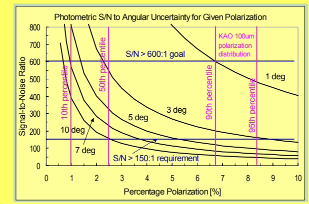
–Angular Resolution – must be comparable to ground-based millimeter wavelength molecular spectral line surveys to enable morphological matching (see Figure at left). Resolutions at, or under, about 2 arcmin are needed.

–Sensitivity and Dynamic Range – must be adequate to enable accurate polarization measurements from 2-20,000 MJy/sr surface brightness. Calculations for SOFIA, balloon altitudes, and space (see Figure below) show that only from space can the faintest regions be probed with FIR polarization. Large-area surveys of modest brightness also need space-based sensitivity.

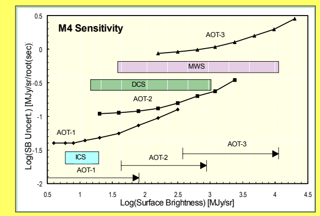


FIR Linear Polarimetry from Space – Constraints to Requirements

–Expected FIR Polarizations – Based on KAO observations and ground-based submm and mm polarization studies, M4-like surveys must be capable of measuring linear polarization of the thermal dust emission to very low levels. From the KAO FIR polarization distribution (see Figure below), a requirement for measuring under 10 degrees position angle uncertainty for an average polarization of 2.5% yields a S/N requirement of 150:1. To achieve under 7 degree uncertainty for 1% polarizations, the instrument must reach a S/N of 600:1.

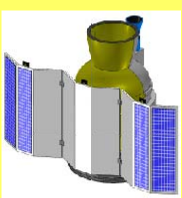


–Surface Brightness Range – Galactic magnetic field surveys face an enormous range of thermal dust emission surface brightness, ranging from the faint infrared cirrus with 1-2 MJy/sr to the galactic center, with a peak surface brightness of 20,000 MJy/sr. This 11 magnitude range is met in the M4 concept through a combination of three data collection rates (0.031, 0.25, and 2 s per read), undersampling of the brightest signal, and coadding of the fainter signals. (see Figure below).



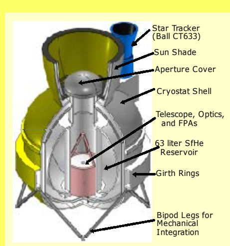
–Wavelengths and Angular Resolution – Ideally, FIR polarization measurements would take place near the peak of the 16-18K cold dust blackbody, around 160-200μm. In SMEX and MIDEX observatories, however, cold telescope diameters are limited to about 20-30 cm (SMEX) and 30-50 cm (MIDEX) by the need for annular cryostats and rejection of Earth- and Sun-shine. In the case of M4, factors of sensitivity, pixel count, cryogen lifetime, and the need for good angular resolution favored operation near 100μm, off the cold dust emission peak. *Higher pixel counts for longer wavelength detectors could shift this balance.*

The Milky Way Magnetic Field Mapping Mission (M4) SMEX Concept



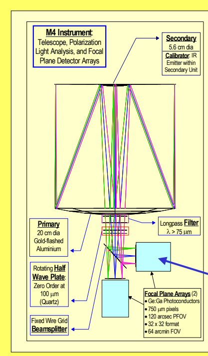
Inside the M4 instrument is a cold, 20cm diameter wide-field telescope, an annular dewar to hold the SfHe cryogen, an ejectable aperture cover, and an instrument/detector bay located behind the aluminum primary mirror. The forward sun shade is sized to reject all earthshine more than 52 degrees away from boresight, while minimizing the warm surface view factor.

The M4 observatory consists of a cold telescope based instrument mounted on a small, high performance 3-axis stabilized spacecraft bus. M4 will fly in a 500km, sun-sync orbit with continuous illumination of its solar panels, avoiding eclipses during its 3-4 month flight. The solar wing also serves to shield the instrument from solar radiation. The forward sun shade and reflective coatings on the cryostat underside reject earth radiation.

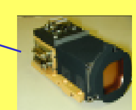


Polarization light analysis consists of a rotating half-wave plate preceding a fixed, 45 degree wire grid which directs the two polarization senses onto two 32x32 Ge:Ga detector arrays. Bandpass action is provided by a long-pass filter and the long wavelength cutoff of the detectors. Detector calibration is performed using frequent (0.07 Hz) flashes from an IR stimulator, located in the telescope secondary reflector.

M4 Array Detectors – SIRTF/MIPS Ge:Ga Clones



The baseline detectors for M4 are identical to the 32x32 pixel Ge:Ga unit in SIRTFs MIPS instrument. These will provide 2 arcmin angular resolution pixels across more than a 1x1 degree instrument field of view. Operating temperature will be between 1.8 and 2.2 K. For QE=0.1, RN=100e/rd, Dark=150e/s, Gain=6 A/W, and well-depths of $3x10^5$ e, the M4 instrument response is 940 e/s per MJy/sr.



Schedule

- The next SMEX call for proposals is slated to be on, or after, January 2003.
- SMEX missions, once selected, must be flown in under 3 years
- FIR detectors for space-based linear polarization detection need to be undergoing testing now in order to be ready for selection and delivery to meet the upcoming SMEX call.